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CAVITY QED OF NV CENTERS IN DIAMOND NANOPILLARS

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14. ABSTRACT

The main objective of this project is to exploit the exceptional spin properties of nitrogen vacancy (NV) centers in diamond to develop a quantum network based on cavity QED of NV centers. While spectacular advances have been made in using RF transitions of NV centers for coherent electron and nuclear spin control, there are considerable challenges for exploiting optical transitions in NV centers. Optical transitions of typical NV centers exhibit excessive spectral fluctuations except for NV centers in ultrahigh purity diamond crystals. To circumvent these difficulties, we have developed a composite microcavity system, in which NV centers in diamond nanopillars couple to whispering gallery modes of the silica resonator.

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TABLE OF CONTENTS

LIST OF FIGURES

1. Summary
The main objective of this project is to exploit the exceptional spin properties of nitrogen vacancy (NV) centers in diamond to develop a quantum network based on cavity QED of NV centers.

2. Introduction
While spectacular advances have been made in using RF transitions of NV centers for coherent electron and nuclear spin control, there are considerable challenges for exploiting optical transitions in NV centers. Optical transitions of typical NV centers exhibit excessive spectral fluctuations except for NV centers in ultrahigh purity diamond crystals. It is also difficult to fabricate diamond-based optical resonators with high finesse.

3. Methods, Assumptions, and Procedures
To circumvent these difficulties, we have developed a composite microcavity system, in which NV centers in diamond nanopillars couple to whispering gallery modes (WGMs) of a silica resonator as shown schematically in Fig. 1.
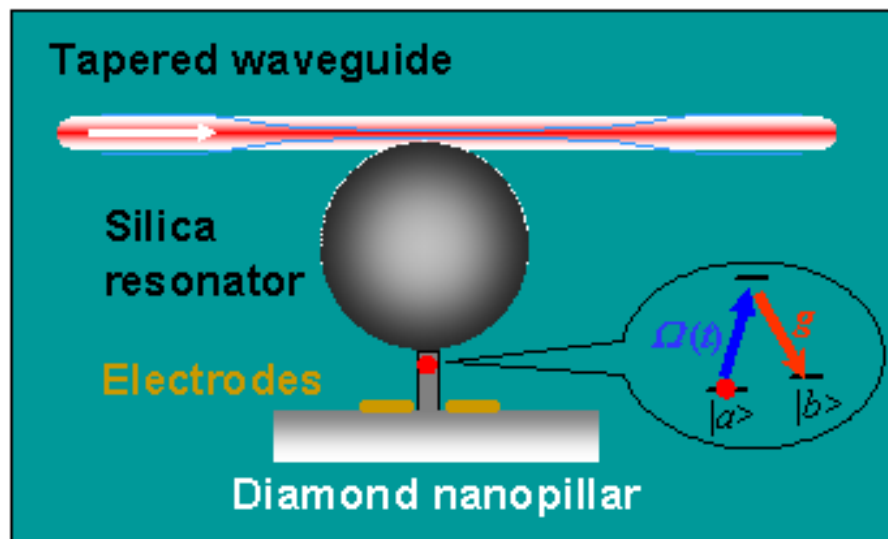

Figure 1   Schematic of NV centers in a diamond nanopillar coupling to WGMs in a silica microresonator.

4. Results and Discussions

a) Enhancement of evanescent decay length with a deformed resonator

For composite cavity QED systems based on evanescent coupling, the NV centers need to be positioned within the evanescent decay length of the diamond surface. We have pursued two different approaches to accomplish this. One is to enhance the evanescent decay length by using a deformed resonator and the other is to implant nitrogen near the diamond surface.

In a WMG resonator, the evanescent decay length, l_e, depends strongly on the angle of incidence. Maximum l_e occurs when the angle of incidence approaches the critical angle θ_c. Our earlier studies have shown that in a slightly deformed, non-axisymmetric silica microsphere, the angle of incidence become closest to θ_c in regions 45° away from either the major or minor axis [1].

We have fabricated silica microspheres by heating an optical fiber tip using a CO_2 laser. Deformation is induced by heating a microsphere from two opposing sides with a 20 ms CO_2 laser pulse. The degree of deformation is controlled by adjusting the intensity of the laser pulse. We have used the dependence of Q-spoiling, induced by a diamond nanopillar, on the pillar-sphere separation as a direct measurement of the evanescent decay length (see Fig. 2). Detailed experimental studies have shown that evanescent decay length in regions 45° away from a symmetry axis is of order 400 nm (with λ=800 nm), which is nearly 4 times of the evanescent decay length of conventional silica WGM resonators with no deformation [2]. For the deformed silica resonator, the WGMs can couple efficiently to NV centers within 200 nm of the diamond surface.
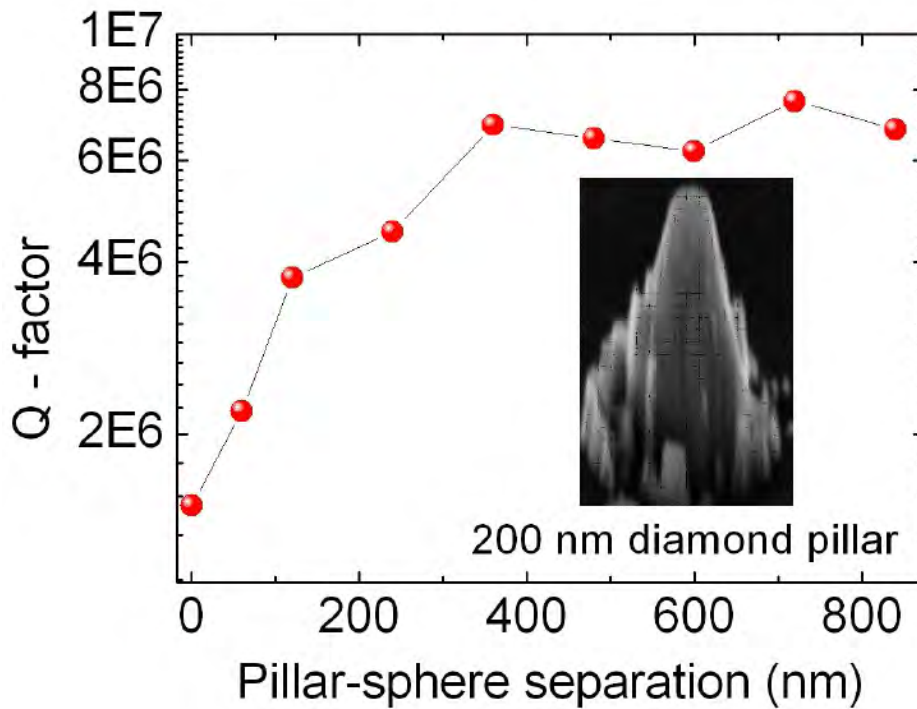

Figure 2 Q-spoiling induced by a 200 nm diamond nanopillar as a function of the pillar-sphere separation. The pillar is positioned in a region 45° away from a symmetry axis of a silica microsphere with d=40 μm and with 2% deformation. The measurement indicates an evanescent decay length of order 400 nm.

<u>b) Implantation and characterization of NV centers near the diamond surface</u>

We have carried out experimental studies to implant nitrogen and to generate NV centers near the diamond surface. Figure 3 shows the repeated scans of photoluminescence excitation spectra (T = 10° K) of the zero-phonon line (ZPL) from a single NV center after the nitrogen implantation. As shown in the figure, the zero-phonon emission from the implanted NV center exhibits spectral fluctuations that are much greater than the intrinsic zero-phonon linewidth. Based on these studies, we have discontinued nitrogen implantation efforts and have chosen to focus on the approach of deformed resonators.
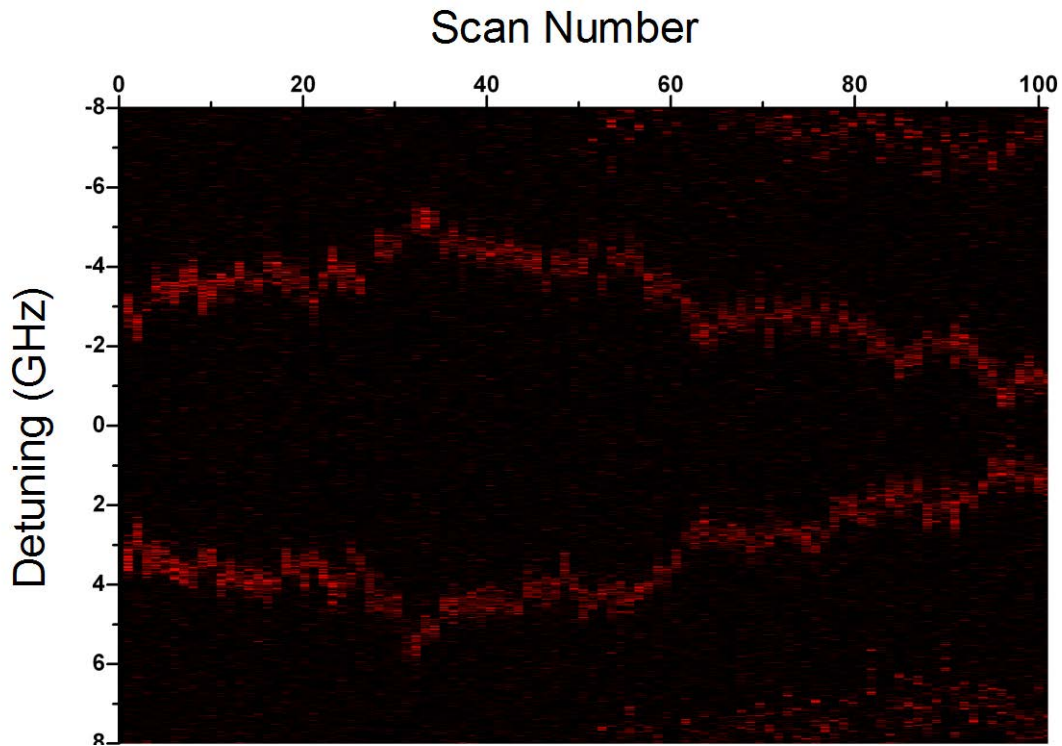

Figure 3 Photoluminescence excitation spectra of the zero-phonon line from a single NV center in an ultrahigh purity diamond nanopillar after the nitrogen implantation. The laser scanning range is 8 GHz. Results from both forward and backward scans are shown in the figure. The data were obtained at 10° K.

c) Fabrication of diamond nanopillars

Theoretical analysis of our earlier experimental results on the composite microcavity of diamond nanopillar and silica microsphere has shown that in order to minimize Q-spoiling induced by the diamond nanopillar and to achieve adequate Q-factor for cavity QED studies, nanopillar diameters need to be below 140 nm [3]. We have fabricated diamond nanopillars at Argonne National Labs and have obtained high quality nanopillars with diameters ranging from 100 nm to 500 nm.

d) Emissions from a composite nanopillar-microsphere system at low temperature

For cavity QED studies at low temperature, the composite nanopillar-microsphere system was mounted on the cold finger of a helium flow cryostat. A crucial aspect of the setup is the positioning of the nanopillar at an equatorial antinode 45^0 away from a symmetry axis. For the precise control of the pillar position, we have incorporated a 3D nano-positioning stage into the cryostat. Figure 4 shows a photoluminescence spectrum obtained at 150° K from the composite microsphere-nanopillar system, where the photoluminescence was collected via directional emissions from the deformed resonator (see the schematic in Fig. 4) and the pillar was excited directly with a green laser. The photoluminescence spectrum features a periodic WGM structure and shows the characteristic NV zero-phonon resonance along with a spectrally broad phonon sideband. The measured free spectral range (FSR) of 2.9 nm (2100 GHz) is in good agreement with the FSR of a silica microsphere with a diameter of 50 μm. For cavity QED studies at liquid helium temperature, the matching of the WGM resonance with the NV optical transition becomes crucial, as will be discussed in detail in the next section.
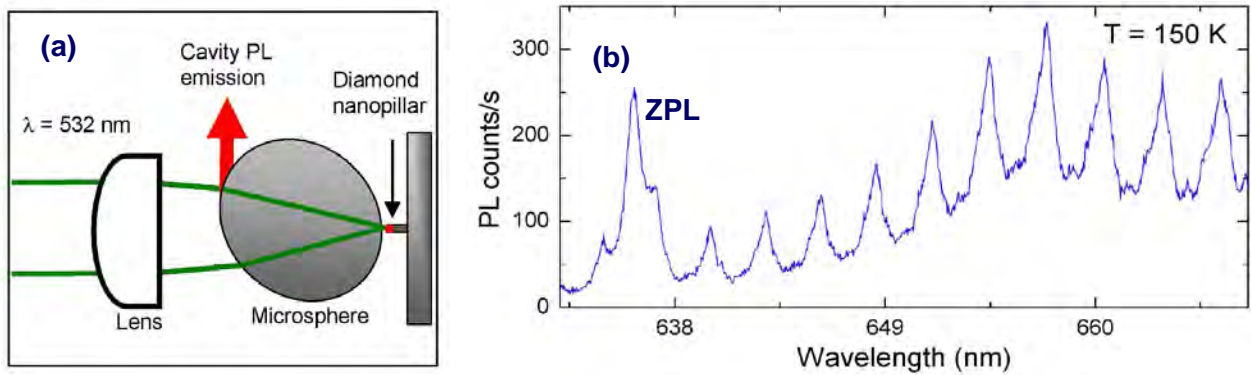

Figure 4 (a) Schematic of NV centers coupling to the evanescent field of a deformed microsphere (deformation is exaggerated for clarity). The emission from the sphere (red arrow) is collected and sent to the spectrometer via free-space optics. (b) Photoluminescence (PL) spectra from the diamond nanopillar coupled to a deformed microsphere obtained at $T=150^o$ K.

e) Frequency tuning of WGMs
An essential requirement for our cavity QED studies is the matching of the cavity resonance with the NV optical transition. In this context, it is ideal that we can tune the resonance frequency of a WGM with a tuning range that covers a significant fraction of its FSR and with a resolution that matches the ultrahigh Q-factor of the WGM.

For frequency-tuning of WGMs, we have used a piezo-driven nano-positioner (from Attocube) to stretch a silica microsphere with fiber stems attached to both poles of the sphere [4]. The slip-stick motion of the nano-positioner enables millimeter long travel ranges at cryogenic temperature. This results in a frequency tuning range of a few hundred GHz. The direct expansion and contraction of the piezo element inside the nano-positioner enables mechanical displacement with a sub-nanometer resolution. With the use of relatively long and thin fiber stems, this leads to continuous frequency tuning with a resolution that is better than 10 MHz.

To fabricate a double-stemmed deformed microsphere (DDSS), we first fabricated a deformed sphere by melting together two conventional microspheres with a CO_2 laser. The degree of deformation was controlled by repeatedly reheating the sphere until the desired deformation (typically < 2%) is achieved. The tip of a bare fiber was then slightly heated and quickly attached to the bottom of the deformed microsphere, forming a DDSS. Figure 5a shows an example of a DDSS with a diameter near 35 μm.

The DDSS was mounted in a Helium flow cryostat, where one stem is held fixed and the other stem is pulled with a piezo-driven nano-positioner, as shown schematically in Fig. 5b. Once mounted in the optical cryostat, the WGMs of the DDSS were excited via a free-space evanescent coupling technique (see Fig. 5c for a schematic) at a wavelength near 637 nm.
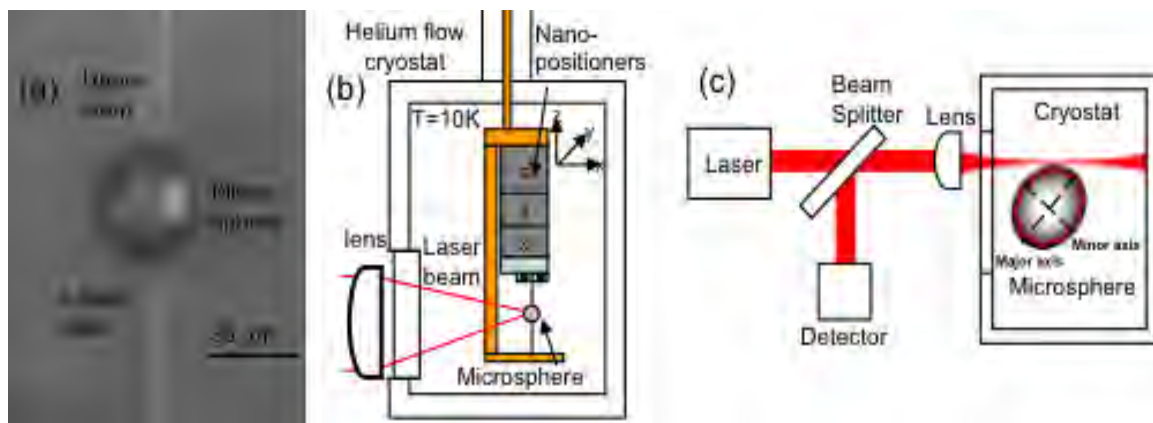

Figure 5 a) An optical image of a deformed silica microsphere with two stems attached to both poles. b) The low temperature set-up. c) A schematic of the experimental setup used for the free space evanescent excitation and detection of WGMs in a deformed silica microsphere

Under the slip-stick operation, WGMs of the silica microresonator can be tuned over a range near 500 GHz. Figure 6a shows an example of this coarse tuning. Note that the step count was not accumulated until the first observation of a frequency shift.
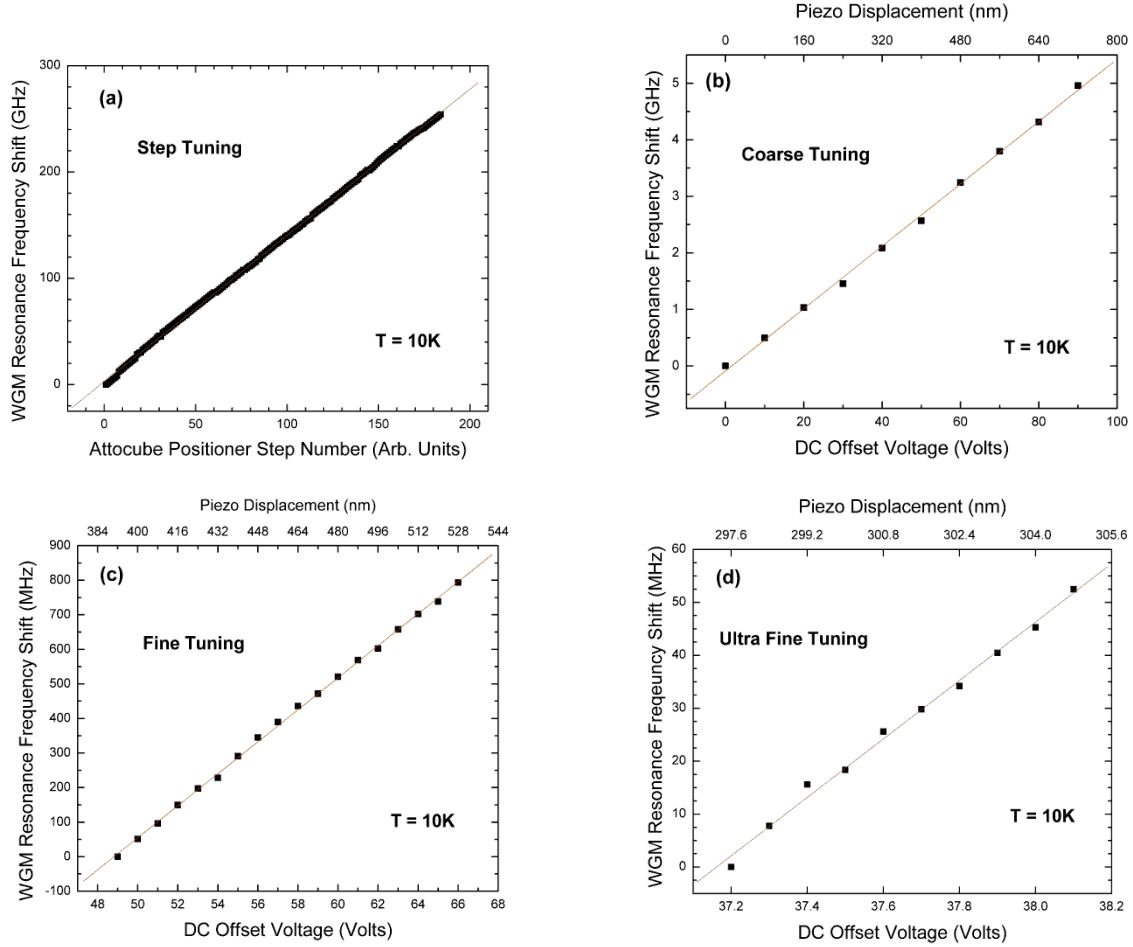
Figure 6 (a) Coarse tuning of the WGM resonance with the Attocube nano-positioner operating in a slip-stick (step) mode, with an external voltage per step of 25 volts. (b)-(d) Fine tuning of the WGM resonance with the Attocube nano-positioner operating in a DC-offset mode; (b) 10 V per step, (c) 1 V per step, (d) 0.1 V per step.

Figures 6b, c, and d display a fine-tuning of the DDSS with direct expansion and contraction of the piezo element. The resonance frequency shift of the WGM can be tuned in 500 MHz, 50 MHz, and 10 MHz steps when the applied voltage steps are 10 V, 1 V, and 0.1 V, respectively. It should be noted that both the coarse and fine tuning processes are reversible and there was little "backlash" in shifting the resonance frequency of the WGM back to a previous position. We also found that the clamping or stretching of the two stems did not alter the Q-factor of the WGM. Note that the ultrafine tuning resolution shown in Fig. 6d corresponds to sub-picometer changes in the sphere diameter. This control of the mechanical displacement at a sub-picometer scale is enabled by the use of relatively long and thin fiber stems, which reduces the effective Poisson ratio of the combined sphere-stem system to approximately 0.0005. The use of long thin stems also allows for the precise positioning of the microsphere relative to diamond nano-pillars fabricated from bulk diamond crystals, which is important for carrying out the cavity QED experiments.

5. Conclusions

This project exploited the exceptional spin properties of nitrogen vacancy (NV) centers in diamond to develop a quantum network based on cavity QED of NV centers. The following journal articles resulted from this research:

Russell J. Barbour, K.N. Dinyari, and Hailin Wang, "A *Composite optical microcavity of Diamond nanopillar and deformed silica microsphere with enhanced decay length*," Optics Express **18**, 18968 (2010).

K.N. Dinyari, Russell J. Barbour, and Hailin Wang, "*Mechanical tuning of whispering gallery modes over a 0.5 THz tuning range with MHz resolution in a silica microsphere at cryogenic temperatures*," Optics Express **19**, 17966 (2011).

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2) Russel J. Barbour, K.N. Dinyari, and Hailin Wang, Opt. Express **18**, 18968 (2010).

3) Mats Larsson, K.N. Dinyari, and Hailin Wang, Nano Letters **9**, 1447 (2009).

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LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

DDSS   Double-stemmed deformed microsphere

FSR   Free spectral range

NV   Nitrogen vacancy center

PL   Photoluminescence

QED   Quantum Electro-Dynamics

RF   Radio frequency

WGM   Whispering gallery modes

ZPL   Zero-phonon line